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A DIGITAL FILTER TECHNIQUE FOR ESTIMATING SMALL-SCALE STRUCTURE OF SALINITY, TEMPERATURE, AND SOUND SPEED

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motions of the ship, variations in suspension cable winch speed, and velocity of underwater currents.

The problem discussed is the removal of the noise from the data without removal of the small-scale structure. To accomplish this, each variable, e.g., salinity, temperature, and sound speed, is treated as a time series and the techniques of spectral analysis are employed to establish a cutoff frequency, f_c . Using this as a criterion, a digital filter was designed to remove the noise from the data. Criteria are presented for the design and use of digital filters to remove the noise and improve resolution of STD/SV digital cases.

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SUMMARY

A series of vertical profiles of temperature, salinity and sound speed was made from a surface vessel, using an STD/SV environmental profiling system in water depths of 350 m off Southern California. The data were recorded digitally on magnetic tape at a 0.2-sec sample rate. The spatial resolution of the sensors was degraded by noise introduced into the data by vertical speed variations of the instrumentation package which resulted from wave-induced motions of the ship, variations in suspension cable winch speed, and velocity of underwater currents.

The problem addressed herein is the removal of the noise from the data without removal of the small-scale structure. To accomplish this, each variable, e.g., salinity, temperature and sound speed, is treated as a time series and the techniques of spectral analysis are employed to establish a cutoff frequency, f_c . Using f_c as a criterion, a digital filter was designed to remove the noise from the data. Criteria are presented for the design and use of digital filters to remove the noise and improve the resolution of STD/SV digital casts.

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INTRODUCTION

In the course of oceanographic observations made some 10 miles west of San Diego, the STD/SV was employed at the beginning and at the end of a 3-day exercise aboard the USNS S. P. LEE. Salinity, temperature and sound speed measurements were made using a Plessey Environmental Systems (Bisset-Berman) Model 9040-4C Environmental Profiling System. Hydrographic casts were also made to obtain independent measurements of salinity, temperature and depth. In this paper the results of two pairs of STD/SV profiles of salinity, temperature and sound speed will be discussed, together with the description of a technique used to remove induced noise from the digital data.

There exists in the ocean a small-scale time-dependent structure in salinity, temperature and sound speed (reference 1). This phenomenon first attracted attention during World War II when "scintillation" of sound waves was observed during sonar experiments. Later work with continuous-profiling higher resolution systems revealed the widespread occurrence of layered regions at all depths. The thickness of these layers ranges from a few centimeters to many meters. The horizontal scale of the layers is approximately one thousand times the vertical scale. The layers are nearly homogeneous but are separated by thin sheets having sharp gradients in which fine structure is frequently observed. Two processes are now believed to be responsible for the formation of these layers. These are (1) horizontal and vertical transport by thermohaline diffusion and (2) vertical transport by dynamic instability.

These small-scale fluctuations are of practical importance in at least three fields of endeavor: (1) acoustic wave propagation, (2) ocean mixing and stirring and (3) in bringing nutrient-rich waters into contact with phytoplankton. Therefore, the study of these processes is of fundamental importance in ocean physics as well as in ocean biology.

The STD/SV is capable of filling in the "gaps" between the relatively few discrete measurement points obtained by means of the Nansen cast. Although the STD/SV cannot now resolve the finest structure that exists in the ocean, it is capable of providing useful information (reference 2) for the small-scale features in the few tens of centimeters range.

SPATIAL RESOLUTION

The spatial resolution of the STD/SV sensors is basically determined by the physical dimensions of the sensors (reference 3). For the temperature sensor the effective size is approximately 3 cm. The salinity sensor has a vertical dimension of approximately 10 cm and its induced electrical current field has a vertical extension of approximately 30 cm. For the sound speed sensor the acoustic path between transducers is approximately 10 cm. Therefore,

the smallest fluctuations that can be resolved by the temperature, salinity and sound speed sensors have wavelengths of 5, 30 and 20 cm, respectively, for the three parameters. However, this spatial resolution can only be achieved under very limited situations.

The spatial resolution of the STD/SV sensors can also be limited by the time constants of the sensors and the speed at which the underwater unit is lowered. For this application, the lowering speed was 50 cm/sec and the time constant for the temperature sensor was 0.35 sec. The conductivity sensor and the velocimeter have virtually instantaneous response times. Therefore, temperature fluctuations with a wavelength of approximately 35 cm can be resolved. This value, however, is several times larger than that determined from the sensor size. In near-isothermal water having calm surface conditions with slow drop rates and small temperature gradients, spatial resolution of this order can be achieved. Under normal operating conditions, however, it will not be possible to obtain a figure even approaching this value because of several purely physical phenomena directly related to cable motion. For example, wave-induced motions of the ship, variations in the cable winch speed, and fluctuating velocities of underwater currents cause the underwater sensor package to sink at a nonconstant rate; therefore, degradation of sensor spatial resolution results. Also, the sensor digital output does not increase monotonically with depth because the sampling rate exceeds the accuracy of the depth sensor; this causes values of salinity, temperature and sound speed to be assigned to the wrong depths. Further, reversal of the sensor package results in mixing of the local water, i. e., turbulence created by the top of the ascending package creates an artificially unstable water condition at the sensor location (bottom end), whose data are recorded as though the condition were normal.

Under normal applications the effective resolution of the temperature sensor is not limited by the sensor size but by the lowering rate and the induced noise. In order that the limiting factor be sensor size rather than response time, it is necessary that the product of the sensor response time and the lowering rate be smaller than the effective physical dimension of the sensor. For the salinity and sound speed sensors, resolution is basically limited by sensor size and induced noise.

Because of the combined effects of ship-roll, lowering speed, sensor time constants and spatial resolution, interpretation of small-scale structure of salinity, temperature and sound speed is extremely difficult.

FILTERING OF STD/SV PROFILES

To illustrate the importance of the effects discussed in the previous section, a section of the original unprocessed digital output for salinity, temperature and sound speed has been plotted in figure 1. The figure shows numerous loop-like and step-like features for all three parameters. This behavior is characteristic of small drop rates, ship-roll, sensor time constant limitation and high sampling rates.

The object herein is to establish objective criteria to remove the induced noise from the data. To this end, the digital output for each parameter is detrended by removing the depth using a polynomial fit. The resulting residual is treated as a time series having a sampling interval of 200 msec. The spectra for each time series are shown in figure 2 for the depth, salinity, temperature and sound speed. The roll of the ship, with a period of 6.7 sec, is evident in the spectra. The second feature is the high-frequency background noise which is again evident in the spectra. From the spectra two things can be obtained: (1) the period of the ship-roll and (2) a cutoff frequency which will be used to design a digital filter for removal of the high-frequency noise from the data.

In figure 3 the digital output from the depth sensor is plotted against time, using the sampling rate of 200 msec for the time interval. If the underwater sensor package were to be lowered from a motionless surface vessel at a constant velocity and without any pendulum effect, a plot of depth versus time should have a constant slope and display no fluctuations. However, because the ship rolls, causing a winch amplitude displacement, it will in turn give rise to variations in the output of the depth sensor. These variations in depth appear as amplitude fluctuations in this display. Vertical depth excursions of the sensor package introduce noise in the parameter measured. In the data considered herein the measured variances of the depth error multiplied by the square of the vertical temperature, salinity or sound speed gradients are of the same order of magnitude as the observed property variances. Two kinds of amplitude fluctuations are recognized. One is the low-frequency fluctuation associated with the roll of the ship. Nonuniform variations in the acceleration of the loaded cable are probably due to a resonance phenomenon, occurring when the natural frequency of free vibration of the cable corresponds to the frequency of the driving forces. The other fluctuation is high frequency and is associated with the time constant of the depth sensor. The digital output of the depth sensor is filtered using a low-pass digital filter to reject the high-frequency component. The effect of the ship roll is now clearly shown; its period is 6.7 sec.

Using 0.4 Hz for the high-frequency cutoff for the depth and 1.5 Hz for the salinity, temperature and sound speed, the time series is digitally filtered, using a low pass filter. The depth profiles for salinity, temperature and sound speed for one up and two down profiles are shown in figure 4. Comparing these profiles with the unprocessed profile shown in figure 1 it can be seen that considerable smoothing has been achieved by removing the high-frequency instrument noise. The effect of the ship roll is still present, however, as this has not yet been removed from the data. This manifests itself as looping or folding and may be observed in figure 4 at 90 m and at 110 m. The other feature still remaining in the data is the spiking in the salinity profiles, e.g., at 245 m. True salinity spikes resulting from temperature gradients are in opposing sense between the up-cast and down-cast.

SALINITY TRANSIENTS

Transients in salinity profiles are of considerable importance and may have several causes. Three are mentioned here: (1) mechanical interruptions of slip-rings or cable snapping due to improper level-winding equipment on the winch, (2) air bubbles or contaminants passing through the conductivity cell, and (3) difference in time constants between the conductivity and temperature sensors.

The salinity level is obtained from the electrical conductivity of sea water. Electrical conductivity of sea water is a function of temperature, salinity and pressure. Of these variables, temperature is considered to be the most important. Any rapid variation in the temperature with depth has a dominant effect upon electrical conductivity.

The effect of the difference in the time constants of the sensors upon the salinity level will be discussed here because it is believed to contribute most significantly to the temperature variable used in calculating salinity. The electrical conductivity sensor has a virtually instantaneous response time whereas the time constant of the temperature sensor is 0.35 sec. Therefore, the conductivity sensor senses a temperature change before the temperature sensor, and compensates for that change using the wrong temperature information.

Numerous spikes are seen in the salinity profiles shown. These are large salinity spikes having amplitudes of approximately 0.05 percent and occur throughout the profile where large temperature gradients occur. A large group of spikes appears in the upper 50 m in all profiles shown. Although the temperature depth gradient was used to correct for these salinity errors, it is quite apparent that this expression will not produce an adequate correction except under very uniform conditions. This is because neither the drop velocity nor the vertical temperature gradient is accurately known over a sufficiently small interval.

An indication that these salinity spikes are instrumental and not caused by temperature gradient effects may be obtained by comparing the down-cast with the up-cast in the profiles of figure 4. A reversal in sign of the salinity spikes associated with rapid temperature changes can be seen at numerous places. If salinity variations of this magnitude were really present, a reversal in sign would not be expected.

INVERSE SMOOTHING

There are essentially three ways to correct the salinity for rapid changes in the temperature. The first is to use fast-response thermistors. The second is to obtain the electrical conductivity directly rather than to convert the electrical conductivity into salinity inside the electronic package. Having obtained at the same time the temperature field with a fast-response thermistor, compensation can then be made numerically for the difference in the response times of the temperature, salinity and pressure sensors; the salinity can then be calculated from conductivity. Lastly, existing salinity data obtained using the STD/SV can be corrected by using the temperature and its time rate of change rather than the drop velocity and the vertical temperature gradient.

The temperature time rate of change was calculated and used to correct the salinity. The temperature time rate of change and the corrected salinity are shown in figure 5. The time rate of temperature change is negative when the instrument is lowered and positive when the instrument is raised. Large relative peaks in the gradient are seen and these are associated with the regions of most rapid temperature change. The spikes have now been successfully removed from the salinity profiles associated with the temperature gradient. The corrected salinity profiles for the down- and up-cast are smoother and more similar. This is in sharp

contrast to the profiles shown in figure 4 that have not received this treatment. The point of greatest significance here is that the conductivity sensor cannot sense its own velocity and temperature gradient. Rather, the sensor is influenced only by the temperature and its time rate of change.

Figure 6 shows as a function of depth the difference between the calculated V_D and the measured sound speed V_M using Del Grosso's sound speed equation before correcting the salinity for the time rate of change of the temperature shown in figure 5. The Del Grosso equation (reference 4) is used here to calculate V_D because the reported standard deviation is less than 10 cm/sec. The solid trace represents the down-cast and the dotted trace the up-cast. The large values, especially around the depth of 30 m, are associated with the temperature gradient. Indeed, a strong similarity is observed when comparing the temperature gradient profiles shown in figure 5 with the sound speed difference profile shown in figure 6. Hence, it is concluded that the large difference in $V_D - V_M$ is due to the smoothing effect of the temperature sensor. It is known (reference 5) that the thermistor with a constant lag coefficient acts as an exponential process whose effect is to smooth the data. Therefore, in order to restore the temperature time series, it is necessary to smooth the data inversely. For a device that exponentially smooths the data, the differential equation

$$(X - \bar{X}) = \tau(d\bar{X}/dt)$$

holds, where \bar{X} is the smoothed value of the variable X in the time series and τ is the time constant of the thermistor. From this equation one obtains the inverted lag equation

$$X = \bar{X} + \tau(d\bar{X}/dt).$$

In the absence of noise, restoration of the original time series \bar{X} is possible by adding the product of the time gradient of \bar{X} and the time constant τ to the smoothed time series. This has been done with the temperature time series, which was then used to calculate the sound speed difference shown in figure 7. The profiles for the down- and up-cast are now separated by 35 cm/sec to avoid overlap. The dispersion in the sound speed difference is reduced to ± 5 cm/sec, except for the up-cast around the 30 m depth where the dispersion reaches a high value of ± 25 cm/sec. This is associated with the large temperature gradients observed at this depth. However, the reason that the dispersion was not reduced further is probably due to the finite size of the instrument package disturbing the medium in the ascent mode so that the correction applied is not adequate.

CONCLUSIONS

The STD/SV is capable of giving nearly continuous vertical profiles of temperature, salinity and sound speed. However, it is very difficult to establish the physical reality of the small-scale structure in these profiles. These small features can be artificially generated by the combined effects of ship-roll, instrument package lowering speed, and the time constants of the sensors. A technique has been indicated herein for determining the cutoff frequency for the noise, the ship-roll period, and the removal of these effects from the data. The formula given in the STD/SV manual for removal of the transients in the salinity profile should not be used. Instead a plea is made for the direct determination of conductivity and the use of fast-response temperature and depth sensors. If the STD/SV must be used, an effective correction for the difference in the time constants between the thermistor and the conductivity sensor can be made by using the time rate of change of the temperature field. The maximum vertical spatial resolution that can be achieved using the smoothing technique described herein is approximately 70 cm.

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Figure 1.

This figure is an unprocessed digital section of salinity (S), sound speed (SS) and temperature (T) profiles plotted as a function of depth.

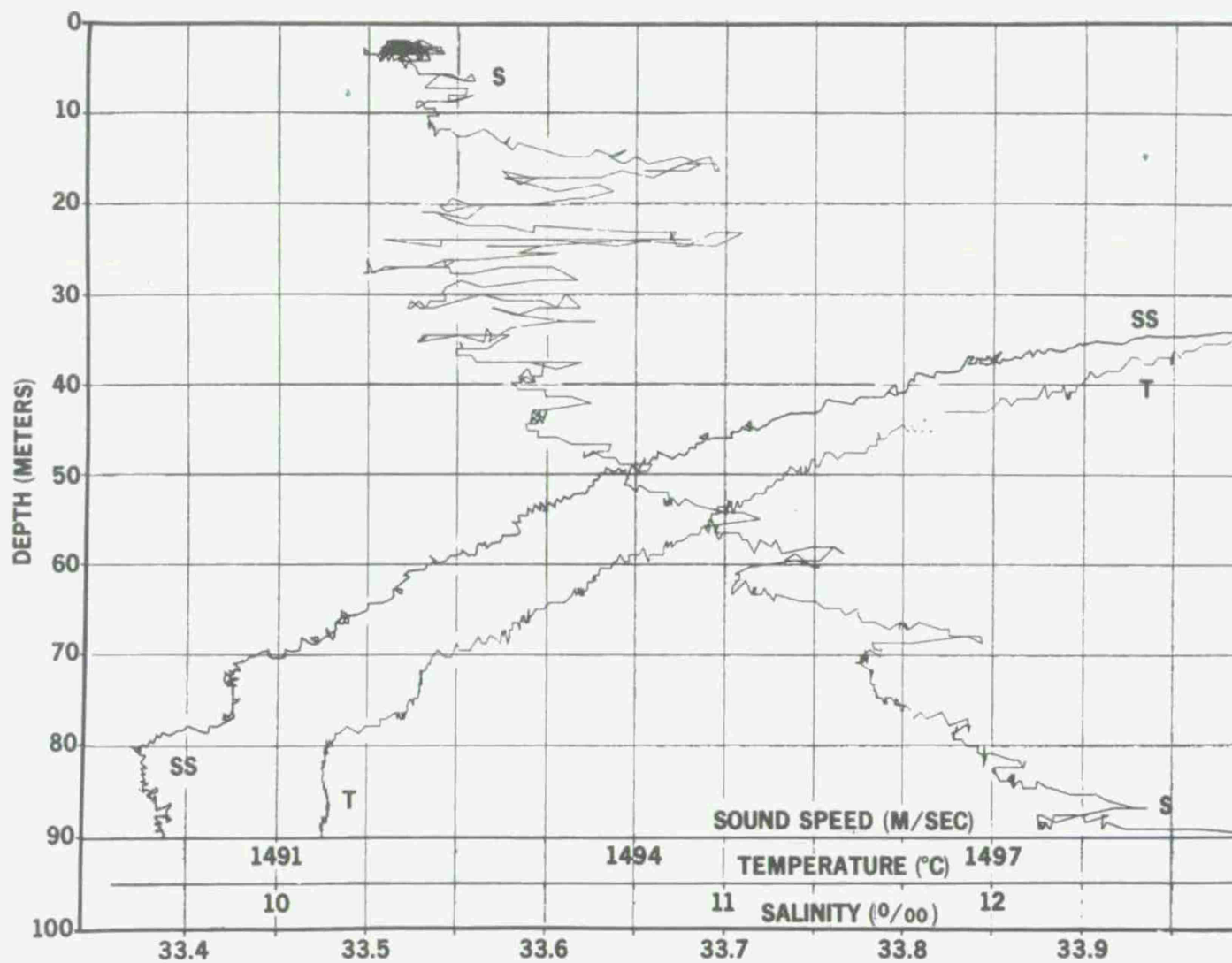


Figure 2.

Power spectral densities for (a) pressure, (b) sound speed, (c) salinity and (d) temperature. The data for each parameter were detrended by removing the depth effect by means of a polynomial fit. The residual data were treated as time series.

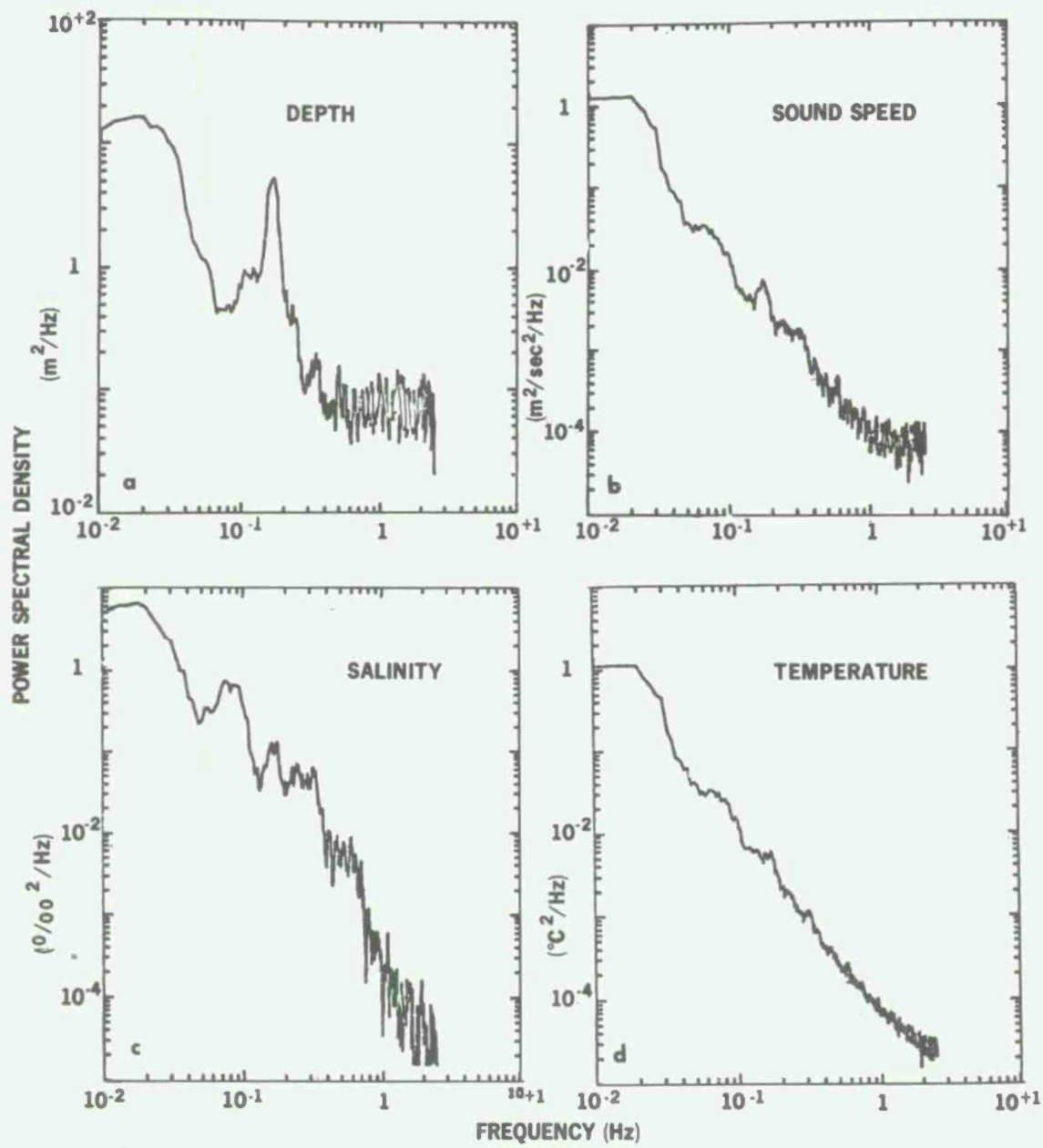


Figure 3.

The unprocessed digital output from the depth sensor is shown as a function of time by curve (a) and the associated digitally filtered output is shown by curve (b). A high-frequency cutoff, $f_c = 0.4$ Hz, obtained from figure 2 was used. The effect of the ship roll can be observed; its period is 6.7 sec.

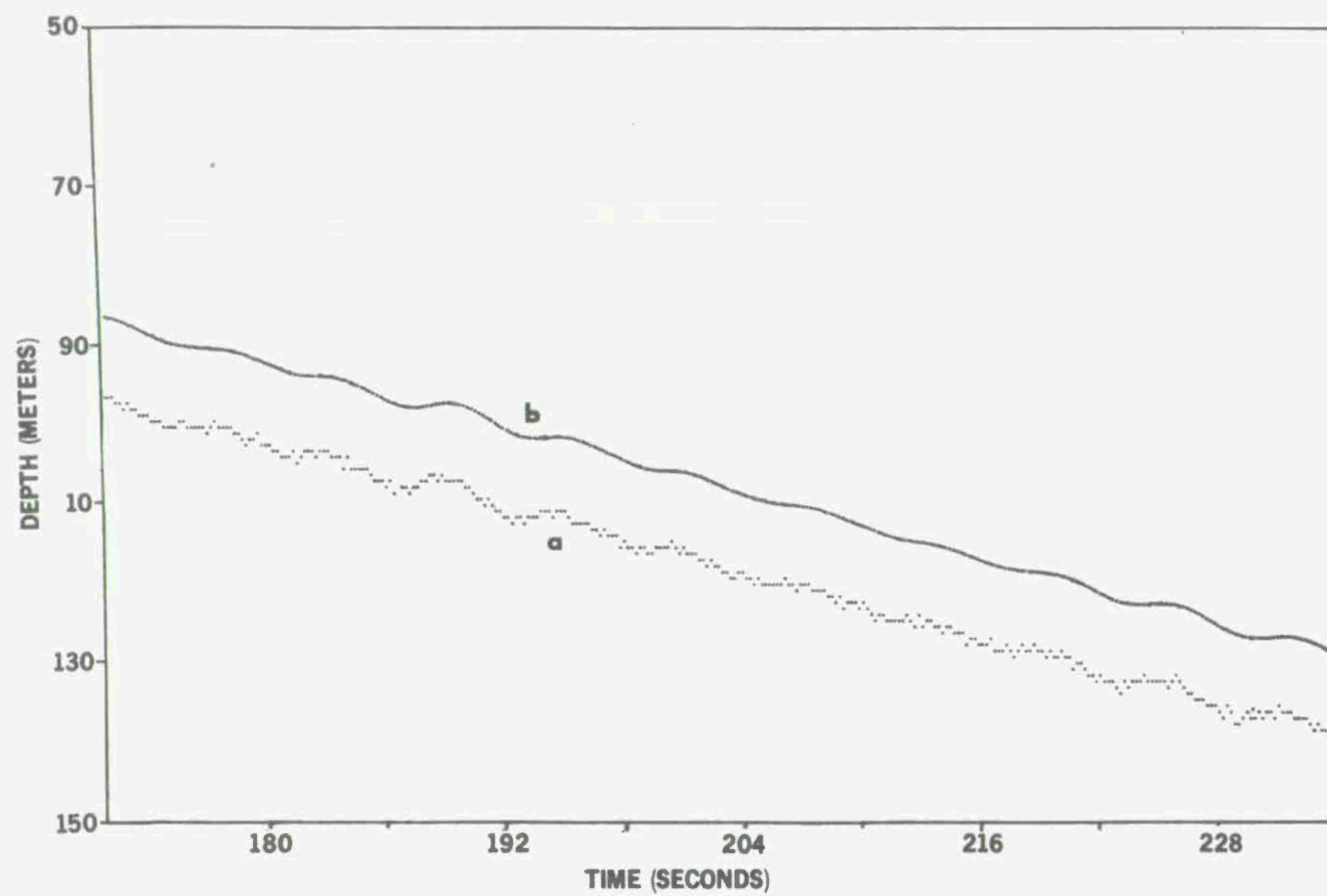


Figure 4.

Vertical profiles of temperature (T), sound-speed (SS) and salinity (S) for the down-cast and up-cast are indicated by downward and upward pointing arrows, respectively. The data were filtered with a digital low-pass filter with a cutoff frequency determined from the power spectral densities shown in figure 2. The scale shown at the bottom of the figure applied to down-cast only. The up-cast was translated to the right by approximately 2°C.

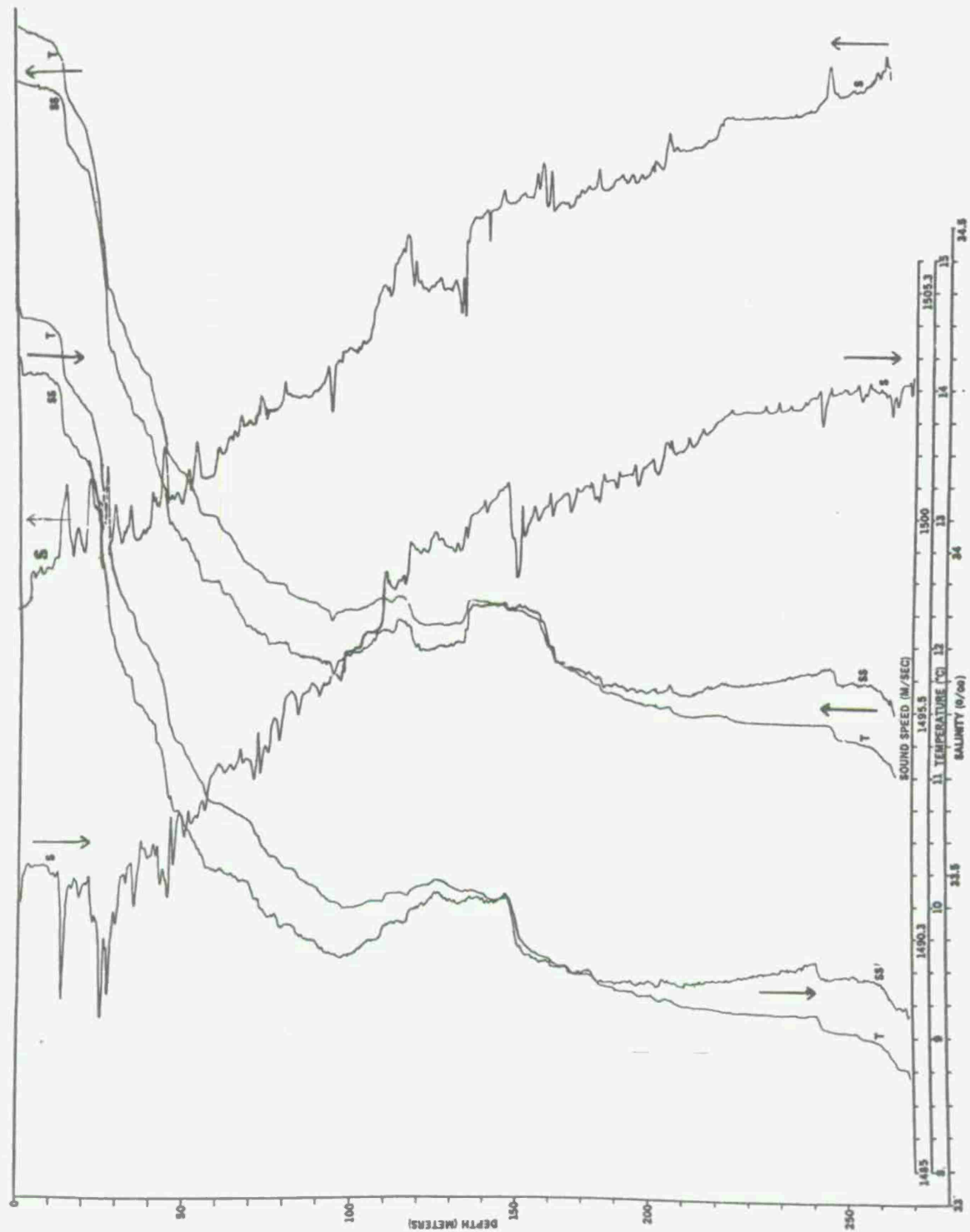


Figure 5.

Corrected temperature (T) and salinity (S) profiles for down-cast and up-cast; cast direction is indicated by the arrows. These are the same profiles shown in figure 4, minus the salinity spikes in the salinity profiles. The time rate of change of the temperature shown at the right part of the figure was used to remove the salinity spikes. The scale at the bottom applies for the down-cast only. The up-cast is translated to the right.

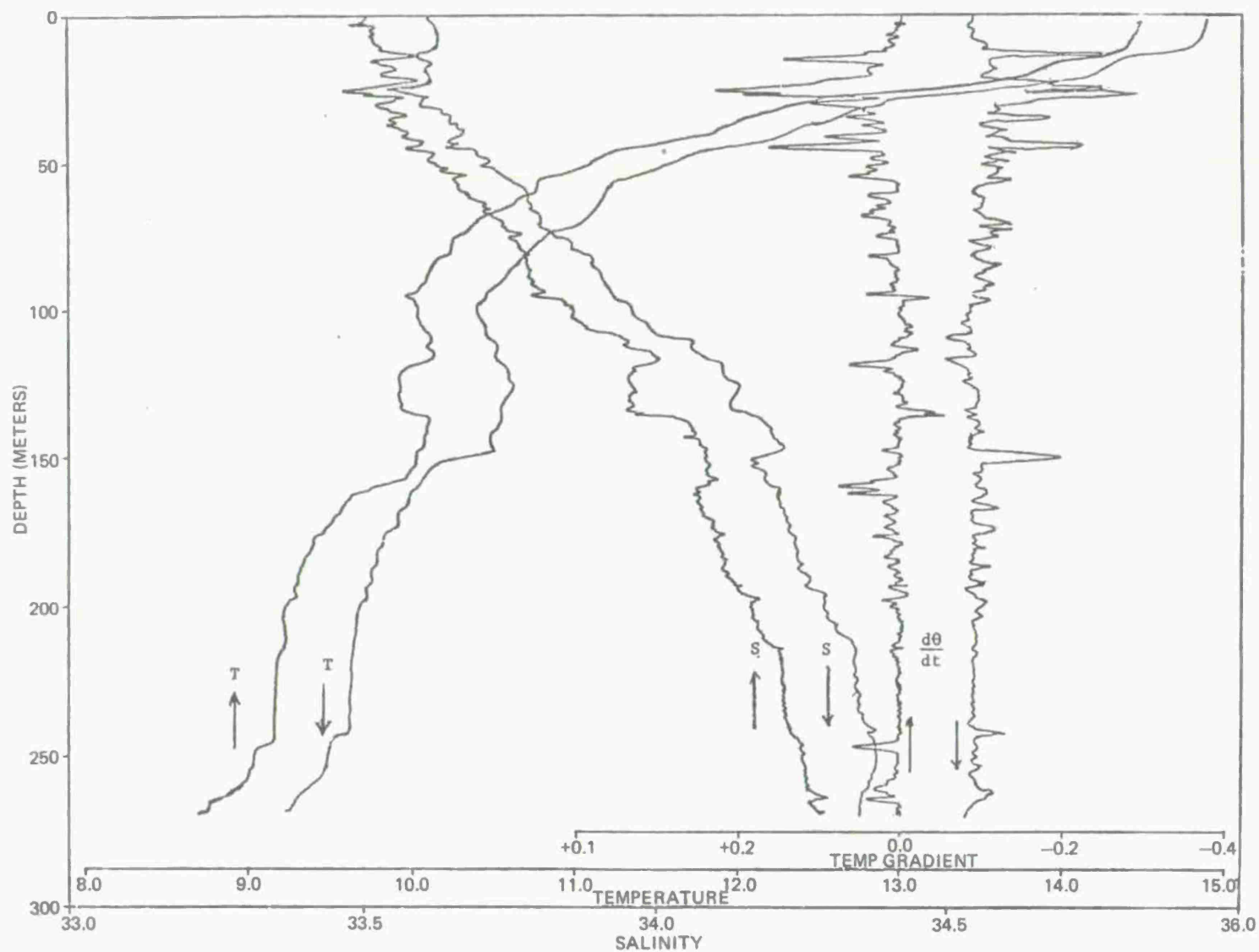


Figure 6.

In this figure the difference is shown between the calculated sound speed (V_D) obtained from Del Grosso's sound speed equation and the measured sound speed (V_M) obtained from the STD/SV for the down-cast and the up-cast. Large differences in sound speed occur whenever the temperature gradient changes rapidly. The salinity profiles were not corrected for the temperature time rate of change.

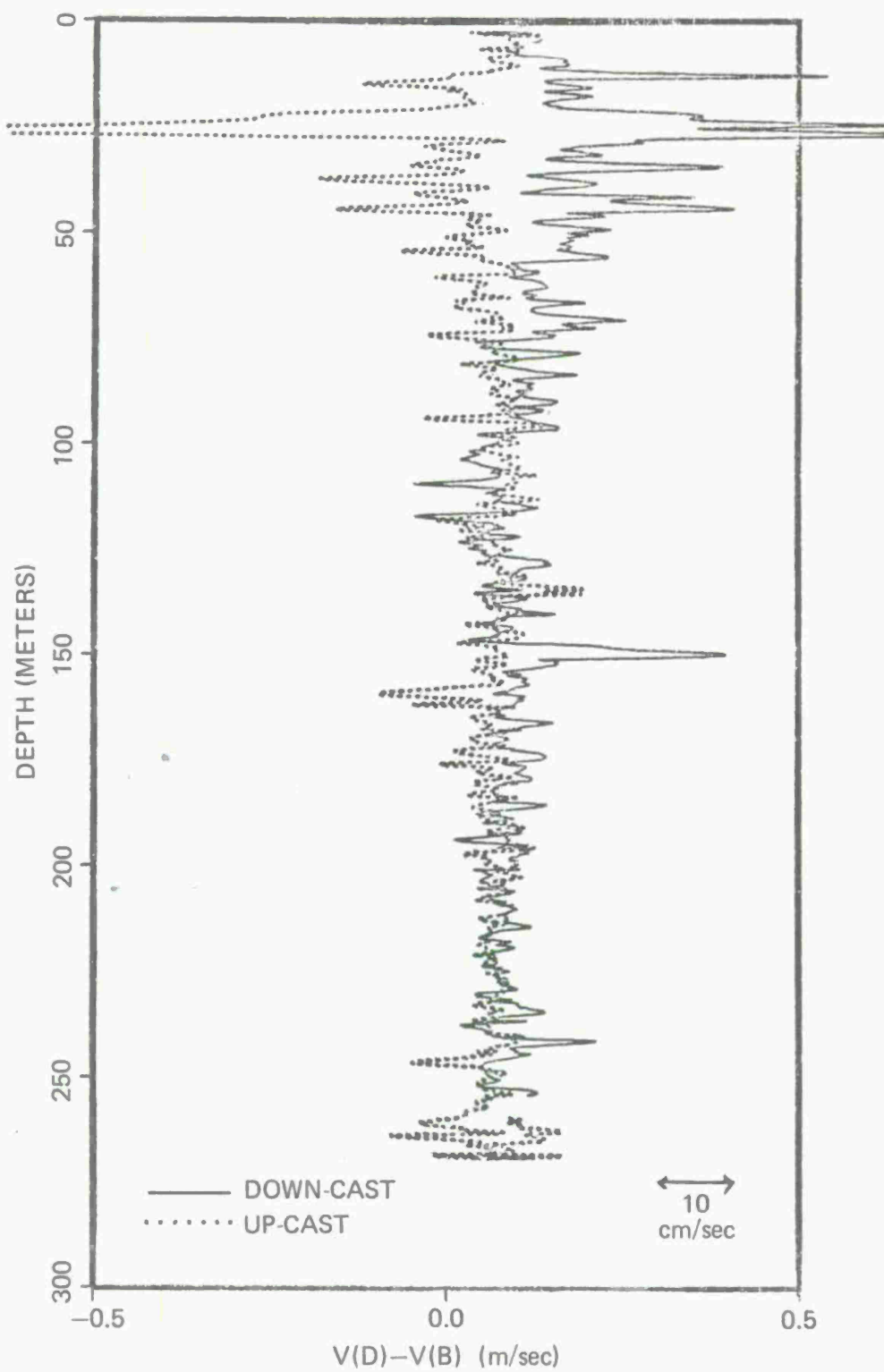
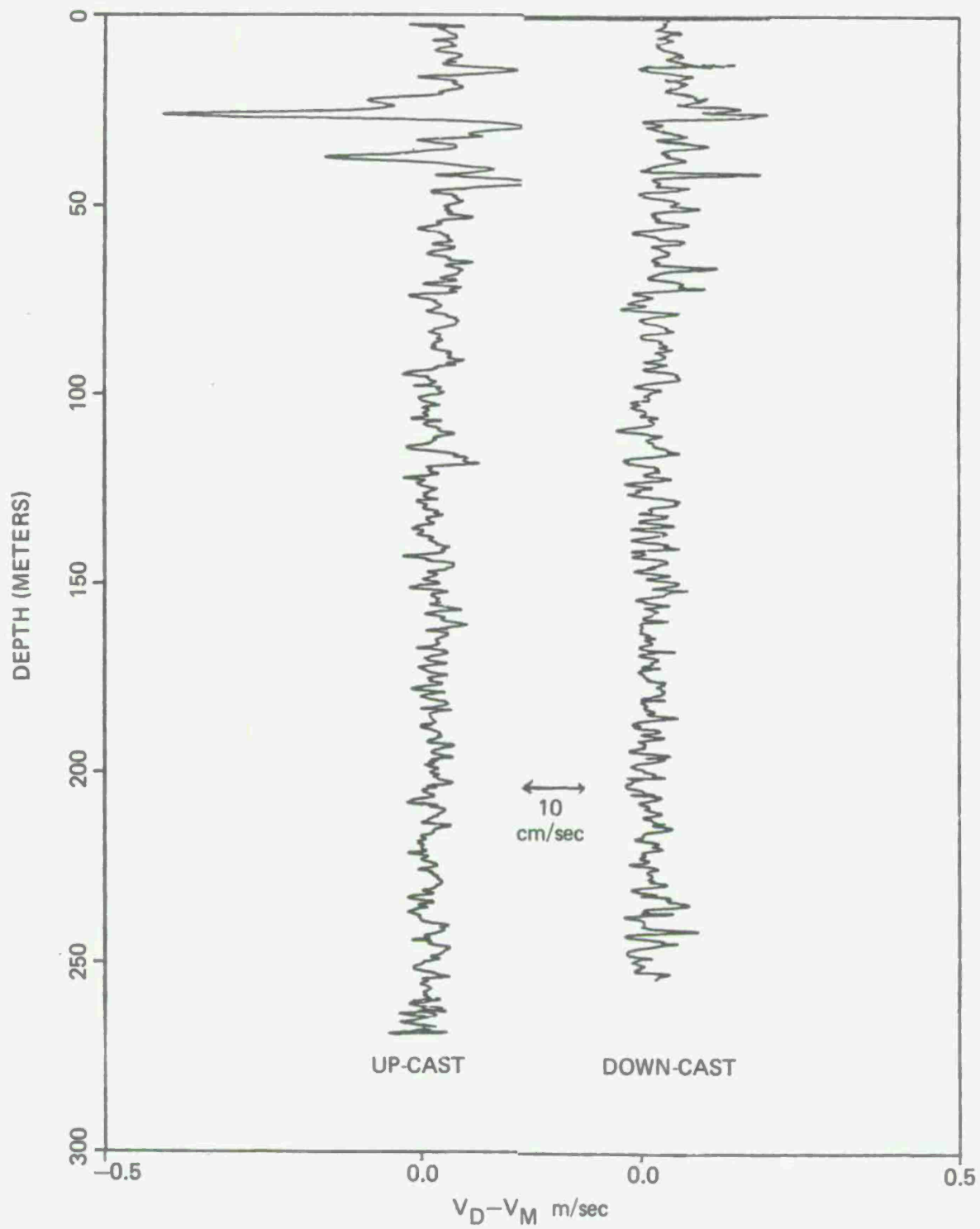
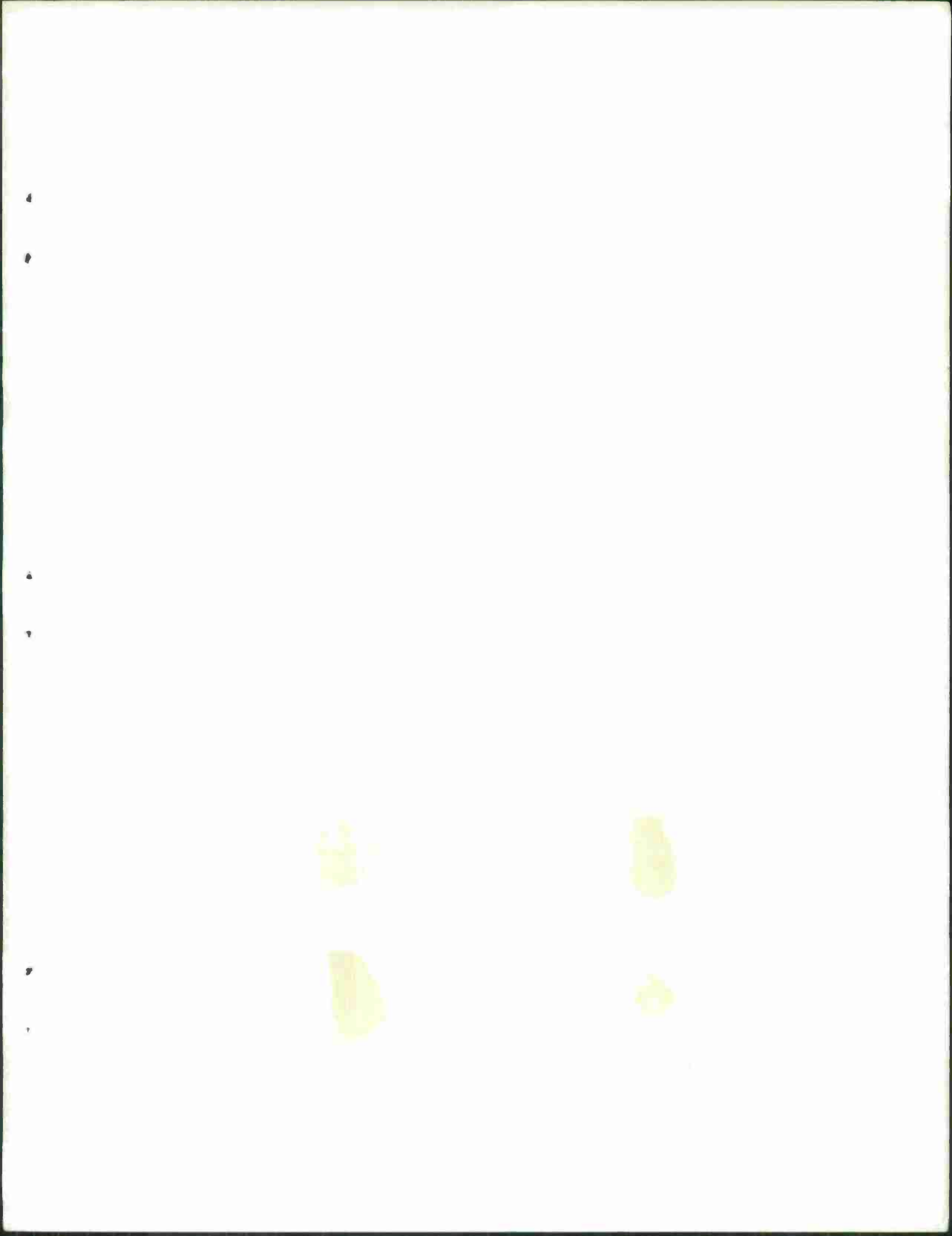


Figure 7.

This figure shows the difference in the sound speed (same as in figure 6) after the salinity spikes were removed from the salinity profiles using inverse smoothing to correct for the temperature time rate of change. The large excursions at about 30 m depth are probably due to the disturbance of the stratified layers by the raising of the STD/SV instrument package. The dispersion in the sound speed is now reduced to ± 5 cm/sec, which is the reported value of the Del Grosso sound speed equation.





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